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# Calibration Factors for DIFAR Processing

*Brian H. Maranda*

**Defence Research Establishment Atlantic**

Technical Memorandum
DREA TM 2001-197
November 2001

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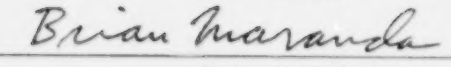

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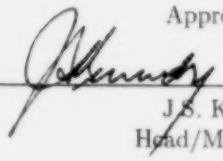

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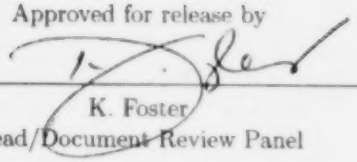

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## Abstract

When processing acoustic data, it is often desired to produce results that are calibrated in terms of standard physical units, such as micropascals. In this note, several scaling factors needed for calibrating DIFAR sonobuoy data are derived. These factors are the acoustic sensitivities of the omni-directional and dipole sensors of the sonobuoy, as defined by the voltage levels at the output of the aircraft radio receiver when the buoy is in an acoustic pressure field of known intensity.

## Résumé

Quand on traite des données acoustiques, il est souvent préférable de donner les résultats étalonnés en unités physiques standard telles que les micropascals. Plusieurs facteurs d'échelle nécessaires pour étalonner des données de bouée acoustique DIFAR ont été établis à partir de la présente étude. Les facteurs représentent les sensibilités acoustiques des capteurs omnidirectionnels et dipôles des bouées acoustiques, définies par les seuils de tension à la sortie du récepteur radioélectrique d'un aéronef quand la bouée se trouve dans un champ de pression acoustique d'intensité connue.

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# Executive summary

## Background

Although most of the signal processing in an operational sonobuoy processor can be carried out in terms of arbitrary units, there are certain processing tasks for which the output must be expressed in standard physical units such as micropascals. An example is the monitoring of ambient noise; it is only by expressing the noise level in standard units that the result can be used in performance predictions, or that comparisons can be made with historical measurements.

## Objective

The objective was to derive several scaling factors needed for calibrating DIFAR sonobuoy data. These factors are the acoustic sensitivities of the omni-directional and dipole sensors of the sonobuoy, as defined by the voltage levels at the output of the aircraft radio receiver when the buoy is in an acoustic pressure field of known intensity.

## Results

The equipment parameters required to derive the scaling factors have to be extracted from two separate documents, the sonobuoy and the receiver specifications, and this information has been brought together in this memorandum. The value of one parameter, the discriminator constant of the radio receiver, was verified experimentally in the laboratory. The calibration factors have been derived from the equipment parameters. It is shown that even when the processing is uncalibrated, the directional channels from the DIFAR buoy must be appropriately scaled relative to the omni-directional channel if beamforming is to be performed.

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# Sommaire

## Contexte

Le traitement de signaux dans un processeur de bouées acoustiques peut s'effectuer en grande partie en unités arbitraires, mais il y a des tâches qui exigent des résultats exprimés en unités physiques standard telles que les micropascals. La surveillance du bruit d'environnement en est un exemple. Ce n'est qu'en exprimant le niveau de bruit en unités standard qu'on peut utiliser le résultat pour prévoir la performance ou qu'on peut faire des comparaisons avec des mesures historiques.

## Objectif

L'objectif était d'établir plusieurs facteurs d'échelle nécessaires à l'étalonnage des données des bouées acoustiques DIFAR. Ces facteurs représentent les sensibilités acoustiques des capteurs omnidirectionnels et dipôles de la bouée acoustique, précisées par les seuils de tension à la sortie du récepteur radioélectrique d'un aéronef quand la bouée se trouve dans un champ de pression acoustique d'intensité connue.

## Résultats

Les paramètres d'équipement qu'il faut pour établir les facteurs d'échelle doivent être tirés de deux documents, les spécifications de la bouée acoustique et celles du récepteur, et ces renseignements sont présentés dans cette note. La valeur d'un paramètre, constante du discriminateur du récepteur radio, a été vérifié expérimentalement au laboratoire. Les facteurs d'étalonnage ont été établis à partir des paramètres d'équipement. On montre que même lorsque le traitement n'est pas étalonné, les canaux directionnels émanant de la bouée DIFAR doivent être correctement pondérés en fonction du canal omnidirectionnel si l'on veut réaliser une formation de faisceau.



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## Acknowledgments

Lloyd Whitehorne set up the test equipment that was used to make the experimental measurements described in Annex A. Don Mosher made some of this equipment available, along with the relevant manuals. Capt. Joe Hood obtained the most recent version of the specification for the AN/ARR-502 receiver.

# 1. Introduction

## 1.1 Purpose

When processing acoustic data, it is often desired to produce results that are calibrated in terms of standard physical units, such as micropascals. In this note, several scaling factors needed for calibrating DIFAR sonobuoy data are derived. These factors are the acoustic sensitivities of the omni-directional and dipole sensors of the sonobuoy, as defined by the voltage levels at the output of the aircraft radio receiver when the buoy is in an acoustic pressure field of known intensity. The sensitivity values are not obvious at first glance, because the signal levels in the DIFAR system are in part described by the frequency deviation of the radio-frequency (RF) uplink from the sonobuoy to the aircraft receiver. The information required to ascertain what voltage level is expected at the receiver output therefore has to be extracted from two separate documents, the sonobuoy and the receiver specifications.

## 1.2 System Overview

The system requiring calibration is the following. The acoustic sensor is an AN/SSQ-53 sonobuoy, commonly referred to as a *DIFAR* sonobuoy. The DIFAR acoustic signals are telemetered to an aircraft via an RF uplink; the device that receives and demodulates the RF signal is the AN/ARR-502 receiver. The acoustic signals undergo real-time processing and analysis aboard the aircraft, where they are also recorded on magnetic tape for post-flight analysis. Calibration factors must be known in order to display the processed acoustic data on a scale labelled with standard pressure units.

Let us consider the nature of the telemetry link in more detail. In the DIFAR sonobuoy, three acoustic channels and two pilot tones are multiplexed to form a *composite* acoustic signal. The RF signal transmitted by the sonobuoy is modulated by the composite signal using frequency modulation (FM); that is, the frequency deviation of the RF signal from its quiescent state is proportional to the instantaneous voltage amplitude of the composite signal. To retrieve the composite acoustic signal on the aircraft, the 502 receiver demodulates the RF signal by generating an output voltage proportional to the frequency deviation at its input.

The advantage of using frequency modulation is that the frequency deviation of the RF signal is largely unperturbed by the amplitude fluctuations that the signal undergoes as the geometry between the sonobuoy and the aircraft changes. Hence the levels of the acoustic signals are accurately maintained by the FM telemetry. However, the derivation of the calibration factors is somewhat involved, because it is necessary to know the constants of proportionality used by the FM modulator and demodulator when converting

voltage to frequency deviation and back again. A further complication is that the gains are not the same for the three acoustic channels.

# 2. The Equipment

## 2.1 Documentation

Throughout this note we shall refer to the specification documents for the DIFAR sonobuoy [1] and the 502 radio receiver [2]. The hardware is updated from time to time, and so before applying the calibration factors derived in this note, the reader should consult the latest versions of these documents to ensure that the work performed herein remains applicable. The methodology should remain valid even if parameter changes are made, since for reasons of compatibility it can be expected that the basic structure of DIFAR telemetry will remain stable until DIFAR goes out of service.

## 2.2 The DIFAR Sonobuoy

There are three acoustic sensors in a DIFAR sonobuoy: an omni-directional hydrophone, and two orthogonal dipoles in the horizontal plane. The dipole channels are called the sine and cosine channels. In forming the composite signal, the omni channel remains at baseband, whereas the sine and cosine channels are translated upwards in frequency using quadrature double-sideband (QDSB) modulation. The sonobuoy specification [1] defines the acoustic sensitivity in terms of the RF carrier deviation as follows:

a. A carrier frequency deviation of ±25 kHz peak shall result when the omni-directional acoustic receiver is placed in a sound field at 100 Hz having an RMS sound pressure level of 122±3 dB above one micropascal.

b. A carrier frequency deviation of ±40 kHz peak shall result when the directional acoustic receiver system is placed in a sound field at 100 Hz having an RMS sound pressure level of 122±3 dB above one micropascal arriving along the maximum response axis of either the sine or cosine channels.

Because the sensitivity is stated in terms of frequency deviation, a useful interpretation of signal levels must include the behavior of the 502 receiver.

## 2.3 The AN/ARR-502 Receiver

The demodulation of an FM signal is performed by a device called a discriminator, which produces an output voltage proportional to the frequency

deviation of the input signal [3]. Of interest here is the constant of proportionality, denoted here by $K_d$, for the discriminator in the AN/ARR-502 receiver. The discriminator constant for the 502 receiver can be deduced from that part of the specification document [2] which defines the receiver output level:

> The output level shall vary linearly within ±5% from 100 millivolts to 2 volts rms when measured across a 10K ohm external resistive load with modulation varied linearly from ±3.75 kHz to ±75 kHz peak deviation at a 1 kHz modulation rate.

The discriminator constant is then given by

$$K_d = \frac{2\,\mathrm{V}}{75\,\mathrm{kHz}} = \frac{0.1\,\mathrm{V}}{3.75\,\mathrm{kHz}} = 2.67 \times 10^{-2}\,\mathrm{V/kHz}. \tag{1}$$

As described in Annex A, this value was confirmed by experimental measurements made on two 502 receivers.

# 3. Calibration Factors

## 3.1 Omni-directional Sensor

The discriminator constant is $K_d = 2.67 \times 10^{-2}$ V/kHz for the 502 receiver. The omni channel of the sonobuoy produces a ±25-kHz frequency deviation when excited with the reference sound pressure at 100 Hz, yielding a receiver output of voltage level[1]

$$V_0 \equiv (2.67 \times 10^{-2}\mathrm{V/kHz})(25\ \mathrm{kHz}) = 0.67\ \mathrm{V}.$$

The omni channel of the DIFAR system, starting from the hydrophone in the sonobuoy and ending with the receiver output, can be viewed as a transducer with sensitivity $V_0/P_0$, where $P_0$ denotes the reference sound pressure level (nominally equal to 122 dB re 1 $\mu$Pa). The sensitivity is usually expressed in decibels with respect to a reference sensitivity of 1 V/$\mu$Pa, and has a numerical value

$$\begin{aligned} 20\log_{10}(V_0/P_0) &= 20\log_{10}V_0 - 20\log_{10}P_0 \\ &= 20\log_{10}(0.67) - 122 \\ &= -3.5 - 122 \\ &= -125.5\ \mathrm{dB}. \end{aligned}$$

In summary, the sensitivity of the omni sensor is −125.5 dB re 1 V/$\mu$Pa at 100 Hz, as measured at the output of the 502 receiver. The sensitivity at other

[1] Unless otherwise noted, stated voltages are RMS values.

frequencies is given relative to that at 100 Hz by a frequency response curve that can be found in the sonobuoy specification [1].

A conceptually convenient way to interpret the above calculation is to attribute a sensitivity of −122 dB re 1 V/$\mu$Pa to the omni sensor as seen internally at the sonobuoy, and then to view the telemetry system as introducing a voltage gain of −3.5 dB.

## 3.2 Directional Sensors

Interpreting the deviation specification for the directional sensors is not as easy as for the omni sensor, because the directional signals are frequency multiplexed into the composite signal using quadrature double-sideband (QDSB) modulation. However, an analysis presented in Annex B shows that from the standpoint of the induced deviation on the RF carrier, the multiplexing of the directional channels is transparent. We therefore proceed in our calculation of the sensor sensitivity without regard to the multiplexing procedure.

The RF deviation produced by either directional sensor, when excited with the reference sound pressure along its main-response axis, is given as ±40 kHz. The voltage output of the 502 receiver at the reference level is then

$$(2.67 \times 10^{-2}\text{V/kHz})(40\text{ kHz}) = 1.07\text{ V}.$$

This may be interpreted as a gain of $20\log_{10}(1.07) = 0.6$ dB relative to a 1-V reference level. The on-axis sensitivity of either directional sensor, as seen at the 502 receiver output, is then

$$0.6 - 122 = -121.4\text{ dB}$$

relative to 1 V/$\mu$Pa at 100 Hz.

The on-axis sensitivity of the directional sensors is greater than that of the omni sensor by the factor 40/25 = 1.6, or $20\log_{10}(1.6) = 4.1$ dB. Compensation must be made for this factor of 1.6 even in an uncalibrated system if inter-channel processing, such as beamforming, is carried out. However, compensation is not needed when estimating target bearing using the arctangent function, since any gain factor that is common to the two directional channels cancels out.

# 4. Summary

Calibration factors have been worked out for the DIFAR sonobuoy system. The sensitivity of the omni-directional sensor, as defined by the voltage level at the output of the 502 receiver, is −125.5 dB re 1 V/$\mu$Pa at 100 Hz. The sensitivity at other frequencies is given relative to that at 100 Hz by a frequency response curve that can be found in the sonobuoy specification.

The gain of the directional channels for on-axis signals is greater than that of the omni channel by a factor 1.6, or $20\log_{10}(1.6) = 4.1$ dB, yielding a sensitivity of $-121.4$ dB re 1 V/$\mu$Pa at 100 Hz.

One way to interpret the above results is to assume a sensor sensitivity of $-122$ dB re 1 V/$\mu$Pa within the sonobuoy, and then attribute a voltage gain of $-3.5$ dB (for the omni sensor) or 0.6 dB (for either directional sensor) to the communications link between the sonobuoy and the output of the 502 receiver.

# Annex A
# Experimental Measurements

## A.1 Background

As a check on the written specifications for the AN/ARR-502 receiver, the characteristics of two receivers were measured at DREA. The measurements were undertaken mainly because versions of the specification document [2] dating from the early and mid 1990s described the input/output transfer characteristic as follows:

> The output level shall vary linearly from 10 millivolts to 2 volts RMS when measured across a 500 ohm external resistive load with modulation varied linearly from ±3.75 kHz to 75 kHz peak deviation at a 1 kHz modulating rate.

This specification excited suspicion, for, if these numbers were correct, the transfer characteristic would not extrapolate through the origin. By consulting the latest version of the specification document it was found that the 10 mV figure has now been replaced by 100 mV, making the numbers internally consistent (see Sec. 2.3). However, it was felt that experimental measurements would eliminate any residual doubts about the definition of the output level.

## A.2 Measurement Configuration

Two 502 receiver units were tested, both of which were built by Flightline Electronics. The receivers had serial numbers 94-005 and 99-023, the first of these being a pre-production model. The chassis of a receiver unit houses 16 independent FM demodulator cards, each being tunable to any of the 99 allocated sonobuoy frequencies. (A table that lists the RF frequencies corresponding to channel numbers $1 - 99$ can be found in the sonobuoy or the receiver specification.)

The measurement setup is shown in Fig. A.1. First, a frequency-modulated RF signal produced by a Boonton 1021 signal generator was fed to a pre-amplifier (a Flightline Electronics product). The 502 receiver hardware distributed the output of the pre-amp to all 16 demodulator cards in the chassis. The specific card to be tested was selected by adjusting the RF signal to have the correct center frequency; the other 15 cards were in effect driven with the out-of-band noise from the signal generator. The frequency deviation of the RF test signal was adjustable. The test signal was monitored with a Hewlett-Packard 8594A spectrum analyzer, allowing an independent check on the value of the frequency deviation.

The demodulated output of the card under test was buffered in order to convert the differential output signal of the 502 receiver into a single-ended signal (i.e., to convert from a balanced to an unbalanced output). The buffer was an audio-frequency amplifier also built by Flightline Electronics. The buffer output was fed into a true RMS voltmeter, a Hewlett-Packard model 3403C, the readings of which were recorded manually. In addition, the output was monitored using a Wavetek 5820B spectrum analyzer and a Tektronix 2464B oscilloscope. These last two instruments made it possible to observe visually the quality of the demodulated signal, and also provided independent measurements of the output level.

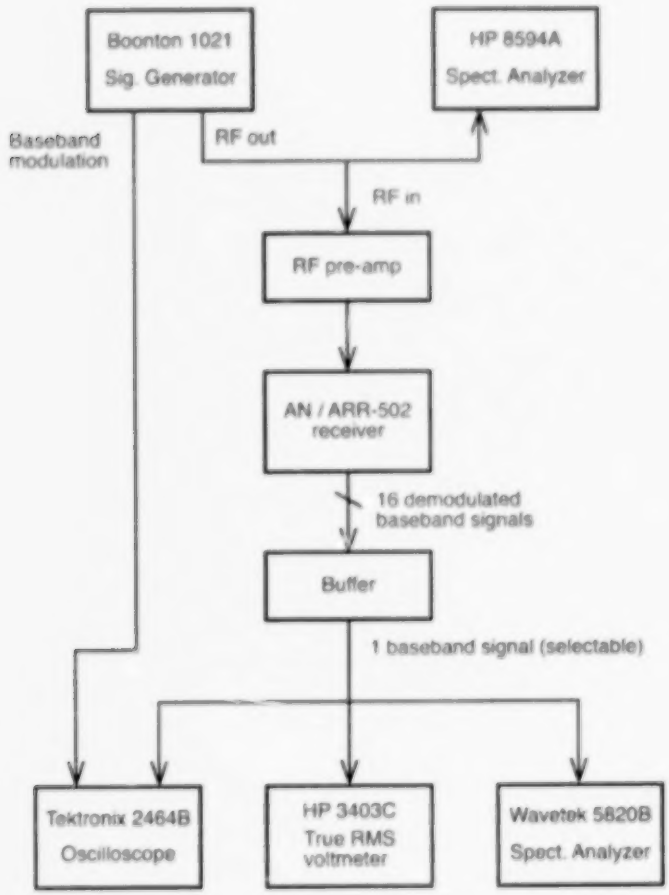


**Figure A.1**: *Experimental setup for measuring the characteristics of a 502 receiver.*

## A.3 Experimental Results

The default configuration of a 502 receiver upon power-up is to demodulate sonobuoy channels 1 to 16, and this assignment was left unchanged. (For simplicity in setting up the experiment, no attempt was made to send command messages to the receiver.) The receiver transfer characteristic was measured for channels 1, 4, and 14 of unit 94-005 and for channel 1 of unit 99-023. The measured output voltages were approximately the same in all cases, agreeing to within a few percent except for small values of deviation (see Remarks below). For this reason, only the measurements for channel 1 of unit 94-005 are presented here. The center frequency of the RF signal was 162.25 MHz; the RF output level was −47 dBm, or 1 mV for a 50Ω system; and the modulating waveform was a 1-kHz sinewave.

Table A.1 gives the measured output voltage as a function of the frequency deviation of the RF carrier. The most accurate measurements are those from the Hewlett-Packard voltmeter, which gave direct readings of true RMS voltage. As a check, the Wavetek spectrum analyzer was also used to measure the dBV value of the 1-kHz peak in the spectrum, but with a much lower accuracy. For easy comparison with the readings from the voltmeter, the measured dBV values have been converted to volts and are listed in Table A.1 to two decimal places. There is good agreement.

The data measured with the HP voltmeter are plotted in Fig. A.2. The open circles mark the individual measurements from Table A.1, and the solid line represents the result of linear regression. Clearly the transfer characteristic of the tested 502 receiver card was highly linear, and extrapolates through the origin as expected. The slope of the line as computed by the linear regression is $2.7 \times 10^{-2}$ V/kHz, very close to the theoretical value computed in Eq. (1). No attempt has been made to quantify the measurement error, as the experimental results are clearly accurate enough to corroborate the input/output relationship given in the specification document.

## A.4 Remarks

1. According to an equipment manual [4], the gain of the audio-frequency amplifier that was used as a buffer is adjustable via jumpers on the circuit cards. It was verified experimentally that the buffer was configured for a gain of unity. For example, at an RF deviation of ±53 kHz the oscilloscope showed a sinewave of 4.0 Vp-p at the output of the buffer. When the two polarities of the differential output of the 502 receiver were examined on the oscilloscope, they were found to be sinewaves of 2.0 Vp-p that were 180° out of phase.

2. The demodulated output waveform was quite noisy when the deviation was low, particularly at ±3.75 kHz, and thus the voltages given in the first few

**Table A.1:** *Measured output from an AN/ARR-502 receiver.*

| Dev. (kHz) | HP 3403C (Vrms) | Wavetek 5820B (dBV) | Wavetek 5820B (Vrms) |
|---|---|---|---|
| 3.75 | 0.106 | −19.8 | 0.10 |
| 5.00 | 0.139 | −17.2 | 0.14 |
| 7.50 | 0.204 | −13.6 | 0.21 |
| 10.00 | 0.271 | −11.1 | 0.28 |
| 15.00 | 0.407 | −7.5 | 0.42 |
| 20.00 | 0.543 | −5.0 | 0.56 |
| 25.00 | 0.678 | −3.1 | 0.70 |
| 30.00 | 0.811 | −1.5 | 0.84 |
| 35.00 | 0.948 | −0.2 | 0.98 |
| 40.00 | 1.084 | 1.0 | 1.12 |
| 45.00 | 1.218 | 1.9 | 1.24 |
| 50.00 | 1.355 | 2.9 | 1.39 |
| 55.00 | 1.492 | 3.8 | 1.55 |
| 60.00 | 1.625 | 4.5 | 1.67 |
| 65.00 | 1.761 | 5.2 | 1.82 |
| 70.00 | 1.898 | 5.9 | 1.97 |
| 75.00 | 2.03 | 6.4 | 2.09 |
| 80.00 | 2.16 | 6.9 | 2.21 |
| 90.00 | 2.44 | 7.8 | 2.45 |

rows of Table A.1 cannot be considered very accurate. However, the quality of the output waveform improved very quickly as the deviation was increased. Since the two DIFAR pilots each generate a deviation of ±7.5 kHz, the demodulated receiver output should be clean when a DIFAR signal is present.

3. The measurements were made with an RF input level of −47 dBm, or 1 mV. An FM receiver should be insensitive to amplitude variations, and it was found that varying the input level between −65 and −10 dBm (between 125 $\mu$V and 70.7 mV) caused the voltage of the demodulated output to change by only 1% or so. Dropping the input level below −65 dBm started to affect the output more strongly. Also, the receiver output level is specified when the FM signal is modulated with a 1-kHz sinewave. Experimentally, the level was found to increase by about 5% when the modulating frequency was increased to 20 kHz. These tests were made on channel 1 of unit 94-005 with the FM deviation held constant at ±40 kHz.

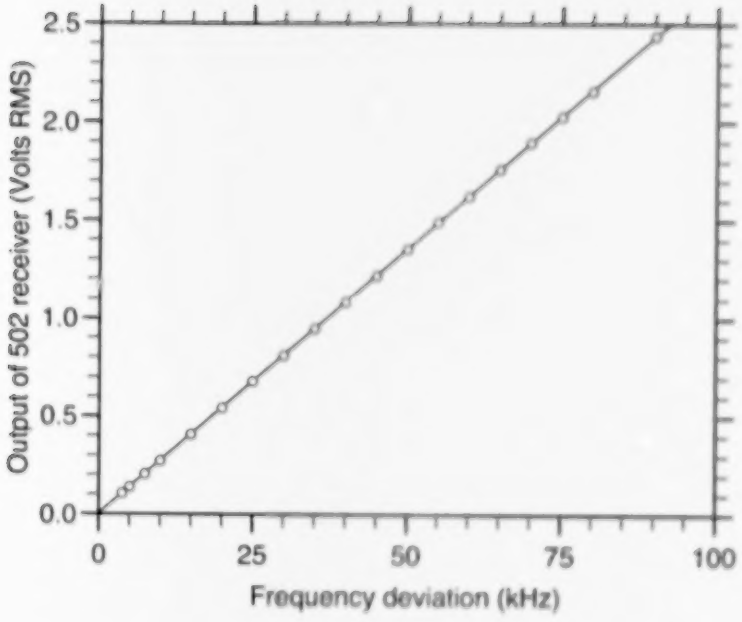


**Figure A.2:** *Measured transfer characteristic of a 502 receiver.*

# Annex B
# Multiplexing of Directional Signals

The interpretation of the ±25-kHz peak deviation for the omni channel is straightforward, as the omni signal is at baseband and the frequency deviation of the RF signal is therefore directly proportional to the signal's voltage magnitude. It is more difficult to interpret the specification for the directional channels, which are frequency multiplexed into the composite signal using quadrature double-sideband (QDSB) modulation. Let us consider the multiplexing procedure in more detail.

For an acoustic wave propagating horizontally and arriving at the sonobuoy at an azimuthal angle $\beta$, the three sensor outputs can be written in the form

$$\begin{aligned} x_o(t) &= x(t) \\ x_s(t) &= x(t)\sin\beta \\ x_c(t) &= x(t)\cos\beta, \end{aligned} \tag{B.1}$$

where the subscripts $o$, $s$, $c$ denote omni, sine, and cosine. The angle $\beta$ is measured clockwise from north; for example, when $\beta = 90°$ the acoustic wave is arriving from the east.

A multiplexer circuit within the sonobuoy forms a composite signal by summing five components: the three acoustic signals, a phase pilot at 15 kHz, and a frequency pilot at 7.5 kHz. The omni channel remains at baseband, whereas the two directional channels are translated upwards in frequency. To generate the RF signal, an FM modulator impresses a frequency deviation on the RF carrier proportional to the instantaneous voltage magnitude of the composite signal. The sonobuoy specification determines the relative gains among the components of the composite signal by allotting a certain frequency deviation to each one. The question is how the magnitudes of the directional channels are converted into RF carrier deviation.

We now begin an analysis which will ultimately show that, from the standpoint of the RF carrier deviation, the QDSB modulation of the directional channels within the composite signal can be ignored. First, we write the phase pilot in the form $\sin(\omega_p t)$, where $\omega_p = 2\pi f_p$ and $f_p = 15$ kHz. According to the sonobuoy specification, the QDSB modulation is implemented by multiplying the directional channels with quadrature subcarriers that have the appropriate phasing relative to the phase pilot. Mathematically, this QDSB signal can be expressed as

$$q(t) \equiv \alpha[x_c(t)\sin(\omega_p t + \pi/2) + x_s(t)\sin(\omega_p t + \pi)], \tag{B.2}$$

where $\alpha$ sets the gain of the directional acoustic receiver system relative to the omni channel, and phases have been inserted in accordance with the specification.

A frequency deviation of $\pm 40$ kHz is produced when an acoustic signal, of the reference pressure level and frequency, arrives along the maximum response axis of either the sine or cosine sensors. These axes correspond to arrival angles $\beta = 90°$ and $\beta = 0°$ respectively, for which the QDSB signal reduces to

$$\beta = 90° : \quad q(t) = \alpha\, x(t) \sin(\omega_p t + \pi)$$

$$\beta = 0° \quad : \quad q(t) = \alpha\, x(t) \sin(\omega_p t + \pi/2).$$

The observation now to be made is that the subcarrier frequency $f_p$ is much greater than the highest spectral frequency in $x(t)$, and hence the envelope of $q(t)$ in both cases above is $\alpha\, x(t)$. Thus the peak voltage of $q(t)$, and in turn the peak frequency deviation of the RF carrier, are determined by the baseband signal $\alpha\, x(t)$.

The preceding analysis can be generalized for an arbitrary arrival angle $\beta$ by substituting Eqs. (B.1) into Eq. (B.2) and then using trigonometric identities to find that

$$q(t) = \alpha\, x(t) \cos(\omega_p t + \beta).$$

From this equation it is easily concluded that, regardless of the value of $\beta$, the peak voltage of the QDSB signal is always that of the omni signal $x(t)$, scaled by the gain $\alpha$. From the standpoint of determining the peak deviation in the RF carrier, the multiplexing of the directional channels within the composite signal is transparent, apart from the gain factor.

The gain $\alpha$ is the ratio of the frequency deviations for the directional and omni channels, and has a numerical value $\alpha = 40/25 = 1.6$, or $20 \log_{20}(1.6) = 4.1$ dB. Although the author is not cognizant of any DIFAR design documents that justify the different scaling between the omni and directional channels, it is not hard to provide a rationale. Under normal operating conditions, the outputs of the three DIFAR sensors are dominated by ocean ambient noise. Because the two dipoles reject much of this noise, their output voltage is reduced relative to that of the omni sensor. For example, in a noise field that is two- or three-dimensionally isotropic, the RMS output voltage of each dipole is respectively 3.0 dB or 4.8 dB less than that of the omni sensor (as measured directly at the sensor outputs). Hence, amplifying the directional channels by an additional 4.1 dB when they are inserted into the composite signal helps to balance the levels of the three channels, and thereby to exploit the dynamic range of the telemetry link.

It should be noted that the mathematical model of the sonobuoy signals has been simplified. It was assumed in writing Eqs. (B.1) that the cosine and sine dipoles point in the north-south and east-west directions respectively. In a field deployment the physical dipoles end up oriented in a random direction, and a compass angle is inserted into the QDSB subcarriers in such a way that virtual dipoles are synthesized in the north-south and east-west directions. The complete mathematical model is unnecessary for the discussion in this note.

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